Test Results for RD3c, a Nb_3Sn Common-Coil Racetrack Dipole Magnet

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Abstract— **The Superconducting Magnet Group at Lawrence Berkeley Laboratory has been developing racetrack technology for economical, high-field accelerator magnets from brittle superconductor. Recent tests have demonstrated 1) robust, reusable, double-layer, flat racetrack, wind & react Nb3Sn coils, 2) a reusable, easily assembled, coil-support structure that can minimize conductor movement, and 3) 15T dipole fields, with no degradation. RD3c is our first attempt to compare measured and calculated field harmonics. A single-layer, Nb3Sn, flat racetrack inner-coil was wound on both sides of a bore-plate, and then reacted and potted (as previously). Hard spacers were wound into the inner coils, to adjust the geometric field harmonics, and identify any problems from hard-spacers. Harmonic measurements with a warm rotating coil also required a considerably thicker bore-plate (for the 35mm OD anti-cryostat). The inner coil-module was sandwiched between two existing outer-coil modules, and pre-stressed within the reusable yoke & shell loading structure. The magnet's performance is discussed, and compared with calculations.**

Index Terms—**Magnets, Superconducting, Nb3Sn, Racetrack, Test Results, Magnetic Measurements.**

I. Introduction

The superconducting magnet group at the Lawrence Berkeley National Laboratory has been developing high-field, superconducting Nb_3Sn magnet technology for future high-energy accelerators. Substantial progress has been made in current density, peak field and cost reduction. D20 demonstrated that Nb_3Sn conductor could be used in an accelerator quality $\cos\theta$ dipole [1]. More cost-effective magnets will be needed for future accelerators. This motivated the exploration of racetrack "common-coil" magnets [2-4]. A series of successful tests demonstrated the ability to control fabrication, assembly and mechanical support [4, 5]. Recent efforts have focused upon assessing the ability of racetrack magnets to achieve higher fields, at less cost, while retaining the reliability and field-quality of $\cos\theta$ magnets.

RD3c, the most recent test in the full-size magnet series, replaced RD3b's small-bore, high-field insert module with a large-bore, harmonic-correction module. The results of this attempt to assess the difficulties associated with achieving good field-quality with flat racetrack coils is reported herein.

Manuscript received August 6, 2002. This work was supported by Office of Science, High Energy & Nuclear Physics, Div. High Energy Physics, U.S. DOE, Contract DE-AC03-76SF00098. All the authors are with Lawrence Berkeley National Laboratory, CA 94720 USA (510-486-4042 or 4572; fax: 510-486-5310; e-mail: lchiesa@lbl.gov, AFLietzke@lbl.gov).

II. Test Preparation

A. Goals and Design Constraints

RD3c was conceived as an economical coil configuration that would assess our ability correct the field errors generated by low-cost, high engineering current-density, flat, common-coil racetrack coils. To be economical, and consistent with common-coil philosophy, the following constraints were imposed: 1) RD3b's outer coils, yoke and shell structure must be re-used. 2) The harmonic-correction insert coils needed to be flat racetrack coils with only one spacer per layer. 3) These insert coils must be fabricated as a rugged independent coil-module that could be inserted between RD3's outer coil modules. 4) No effort would be made to correct the up-down asymmetric quadrupole. 5) Bore-plate access must be large enough to accept a 35mm diameter rotating-coil probe.

To simultaneously test reliability, the insert coil must be constructed with the best rapid-training, reliable insulation technology that could be readily applied. If the training were subsequently discovered to be slow, stick-slip motion diagnostics would be available to localize the slippages.

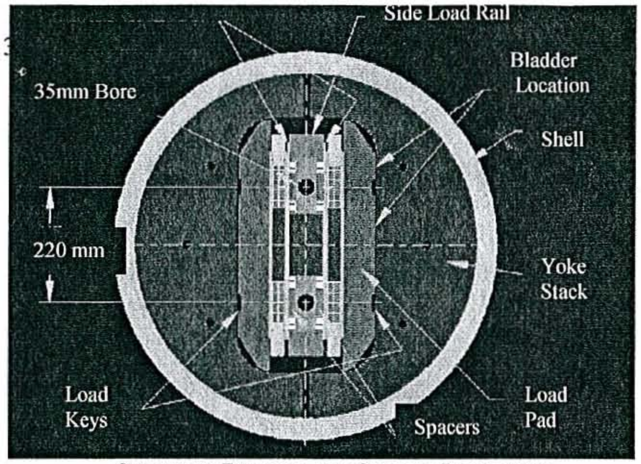
B. Magnet Parameters

Figure 1 shows the magnet cross-section that resulted from the above constraints. The harmonic-correction module was inserted between RD3b's outer coil modules. Like RD3b, the insert module used an aluminum-bronze "bore-plate" to separate two single layer coils that had an internal ramp to reverse the current direction across the bore-plate, without an internal splice. In contrast to RD3b, each coil used a large spacer near the previous field maximum, to counteract the large positive sextupole generated by the outer coils. Each coil had 16 turns in two equal blocks. The bore-plate was thick enough (39.5 mm) to allow access for a 35mm diameter rotating coil probe, while stiff enough to pre-stress the outer coil-block where it crossed the bore hole (nears the ends).

Fig. 1. The magnet cross-section for the RD3c: a harmonic correction, training, and magnetic measurement test.

RD3c's performance limits are compared with RD3b in Table I. RD3c's insert coil used the same cable as RD3b's insert. Being at a lower field, this caused the outer coils to set the magnet's current limitation at 11.9KA.

TABLE I



GEOMETRIC FEATURES AND GENERAL PARAMETERS

MAGNET	RD3c*	RD3b
I_{max} (inner) (KA)	**13.3**	10.8
B_{max} (inner) (T)	**13.1**	14.8
I_{max} (outer) (kA)	**11.9**	10.8
B_{max} (outer) (T)	**11.3**	11.5
$I^{(ss)}$ (KA)	**11.9**	10.8
$B_0^{(ss)}$ (KA)	**10.9**	**14.6**
$J_{cu}^{(ss)}$ (inner) (KA/mm^2)	**1.6**	1.1
$J_{cu}^{(ss)}$ (outer) (KA/mm^2)	**1.6**	1.5

* Calculated values. Training was aborted to assess further training improvements during a later thermal cycle.

Magnet protection system was achieved as previously [4]. Each coil layer had actively powered quench heater strips that were potted in intimate contact with the coil. They could directly heat 60-80% of the turns for several cable widths on both sides of the winding island. Sufficient power could initiate massively parallel quenching within 10ms. An energy dump resistor was available to assist, and was usually adjusted to keep the magnet's terminal voltage below 500V.

C. Diagnostics

Most of the diagnostics (strain gauges, thermometers, fast-flux changes, and quench initiation and propagation were nearly identical to previous tests. For this test, additional effort was focused upon acquiring: 1) reliable field harmonic data, 2) preliminary snap-back measurements at 1 Tesla, 3) a more complete record of the fast flux changes that trigger quenches, and 4) a high resolution picture of turn-turn quench propagation.

The rotating-coil magnetic field harmonic data acquisition and analysis system was essentially identical that used to verify the accelerator quality of D20 [1]. A 40 turn tangential coil, 428mm long, rotated at constant speed (~1Hz) at a radius of 11.7mm. Dual dipole correction coils were wired to provide a high resolution harmonic signal in which the fundamental was significantly attenuated (about 120x). Both signals were amplified with integrating amplifiers, digitized at 1Khz with 24 bit HP3458A DVM's, and Fourier analyzed relative to the fundamental. The resulting harmonics were corrected for all known amplifier and coil harmonic sensitivities, and normalized to a radius of 10mm. Accuracy was checked by comparing the harmonics inferred from measuring our reference permanent magnet, against its 10 year database of measurements.

The fast-flux-change DAQ system for this test used a more reliable triggering system, so as to collect more high resolution pictures of training quench starts, and turn-to-turn quench propagation.

III. Test Results

A. Training Observations

Training begun immediately after establishing that the entire magnet protection system was operating reliably at 2KA. The magnet was ramped to quench with a variety of ramp rates, while being cooled by the 4.4K 2-phase LHe bath maintained by a refrigerator. Training (Fig.1), started at 76% of the short-sample limit, and reached an unexpectedly low plateau (92%), with several small fall-backs. Most training quenches started in the previously used outer coils, not the (virgin) harmonic-correction coils.

QUENCH HISTORY RD3c

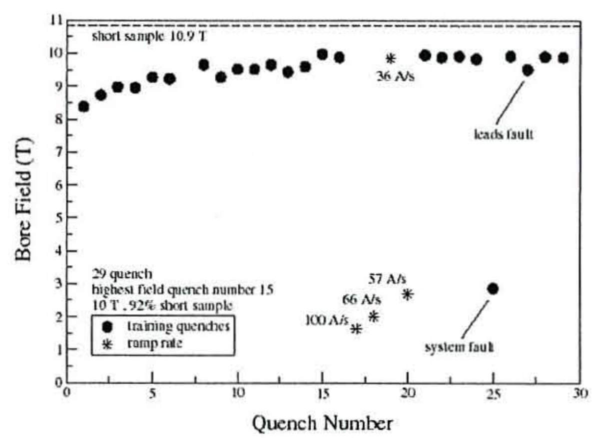


Fig. 1. Bore field as a function of quench number.

All training ramps showed evidence of many "stick-slip" conductor movements (examples in Fig. 2). Most, possibly all, training quenches, especially the "plateau" quenches showed this evidence of conductor movement shortly (1-2ms) before resistance onset. In contrast to previous experience, most of RD3c's training quenches had a massive movement, followed by an extraordinarily fast development of resistance. For Q15 (Fig. 2, dashed), resistance is seen 0.7ms after peak deceleration (~1ms after first peak acceleration). An anomalously rapid rise of the resistive dV/dt, saturating (2000V/s) 1ms after quench onset, implies anomalously rapid quench propagation.

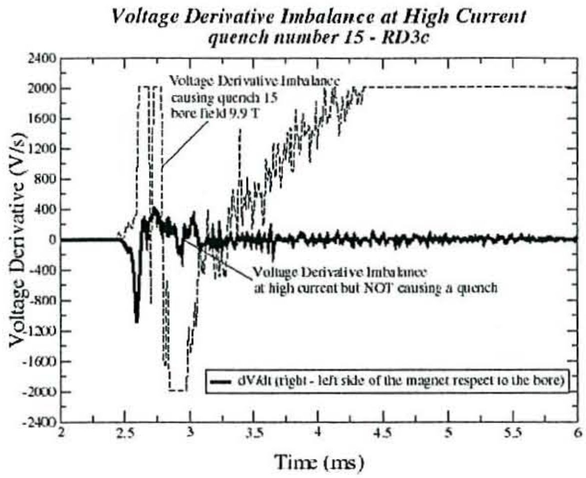


Fig. 2. Two of hundreds of voltage imbalance derivatives observed during ramp Q15, which have been interpreted as "stick-slip-stick" conductor movements. The polarity depends upon the location of the slippage. Most of them are small (bold trace) and cause no problem. The massive one (dashed) occurred immediately before Q15's quench onset.

No significant changes in the relative number of fast-flux changes (FFC's) occurred after the first training quench. Their training had stopped. After quench Q02 "stick-slip" type FFC's started abruptly at 8KA, and could repeat interminably with repeated ramps, irrespective of quenching. Like the quenches, the "plateau" FFC's (thus far analyzed), were equally distributed on both sides of the bore-plate, but only <12% could be attributed to either slippage against the bore-plate, or other relative movement within the insert module. Unlike the quenches, which were about equally distributed between layer-3 and layer-4, their were only very weak flux imbalances observed inside the outer coils.

B. *Miscellaneous Observations*

The 20K Residual Resistivity Ratio (RRR) of the new insert coil was 92. The splice resistances were low (~1 nOhm). The turn-turn propagation delay was 26ms on the first training quench (Fig. 3), but became unrecognizably short for (most) training quenches, where a massive conductor movement appeared to initiate the quench (Fig. 2).

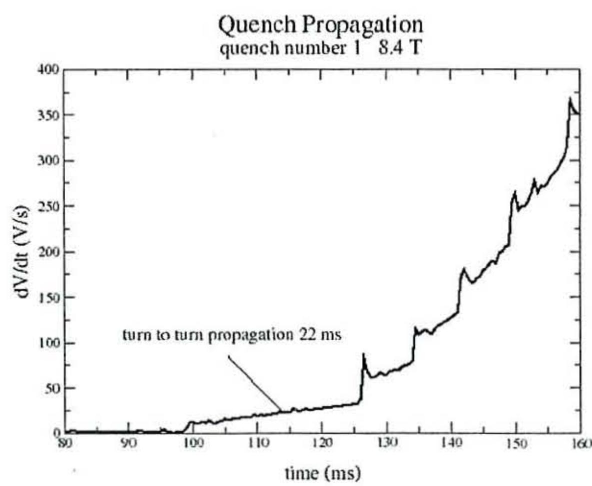


Fig. 3. Voltage imbalance derivative recorded during Q1 ramp.

C. *Ramp Rate Dependence*

The ramp rate sensitivity (Fig. 4) was very similar to most LBNL Nb_3Sn magnets, after the normalized current was plotted versus the rate of change of the bore field. A mild sensitivity at low ramp-rates was followed by a strong drop off around 3-5 Tesla/minute. A low plateau, 10-15% of short sample was observed for faster ramps.

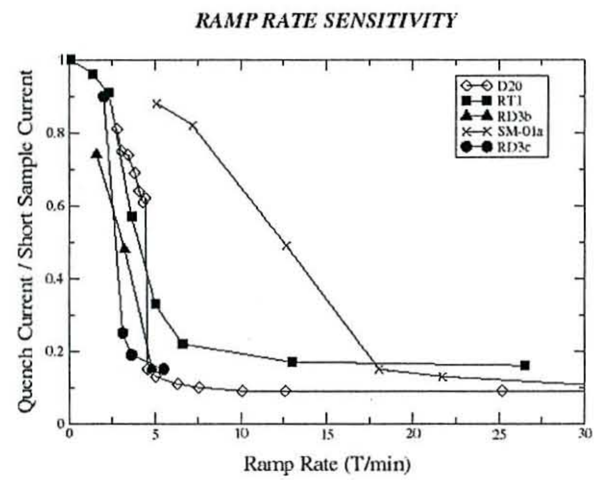


Fig. 4. Normalized quench current vs. ramp-rate of the bore field.

D. *Magnetic Measurements*

Two separate multi-cycle 0-10-0KA ramps were applied to the magnet, to measure the magnet's hysteretic harmonic response to magnet ramping. Both ramp cycles started from a quenched magnet, went to 10KA and back at least twice, and had several pauses to allow estimation of the ramp-rate hysteresis, and a pause at 1kA to observe any "snap-back" that might exist. The "allowed" normalized central integral harmonics (integrated over the coil length at the middle of the magnet), at 90% of "short-sample" are summarized in Table II. The measured sextupole (b3 = -10.39) was 5 units more negative than expected; the measured up-down asymmetric quadrupole (a2 = -15.65) was smaller.

TABLE II
CALCULATED AND MEASURED HARMONICS AT 10KA

Normal	Calculated	Measured*
b_3 (unit)	-5.44	-10.39
b_5 (unit)	-0.24	-0.02
b_7 (unit)	0.58	0.61
Skew		
a_2 (unit)	-31.2	-15.65
a_4 (unit)	-1.56	-1.45
a_6 (unit)	0.01	-0.20

* Averaged over the hysteresis (E-4 units, at 1cm).

The Hall probe measurements in one bore were compared with the peak central field calculations (Fig. 5). The measured and calculated values agreed to within 1%. In the other bore, the peak, average, integrated dipole component from the rotating coil is compared with the 3D calculated, integrals. There is a good agreement at low currents, but at currents higher than 4KA a deviation was observed. The difference was nearly 4% at 10kA.

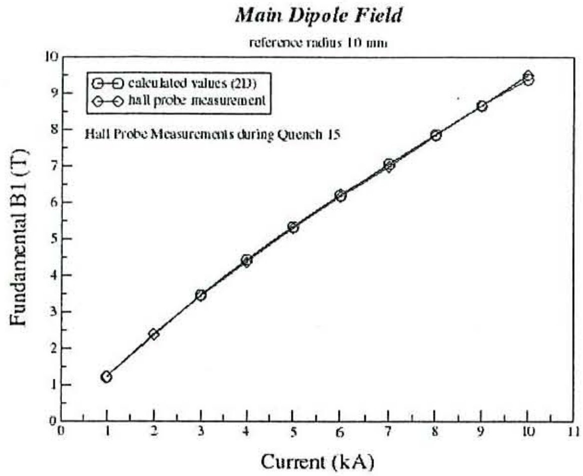


Fig. 5. Main Dipole field B1 as a function of current. Calculated central field values are compared with measurements taken with the Hall probe.

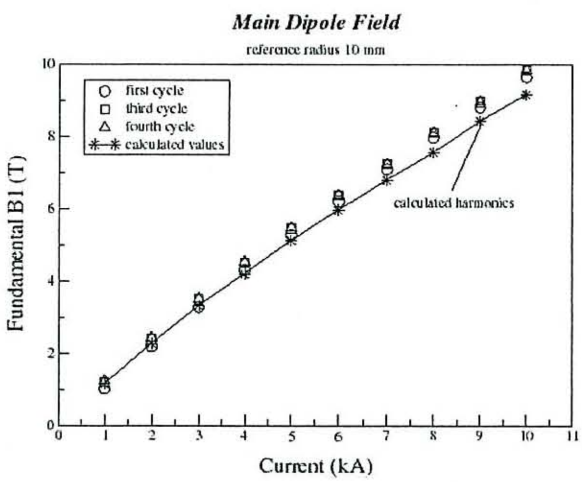


Fig. 6. Main dipole field B1 values deduced from the rotating coil; versus magnet current. The calculated values were computed by averaging the fundamental's axial dependence over the same length.

The central 43cm integral harmonics were measured "on the fly" for the complete ramp cycle, and showed very little scatter (within one ramp). Ramp to ramp variations were much bigger. The normalized central integral sextupole (Fig. 7) illustrates the quality of the data during a third ramp cycle. A 15 min pause at 1.2KA for snap-back measurements. Ramping re-started with a ramp rate of 30A/s for an entire cycle. At 10 kA a fairly large spread was still present

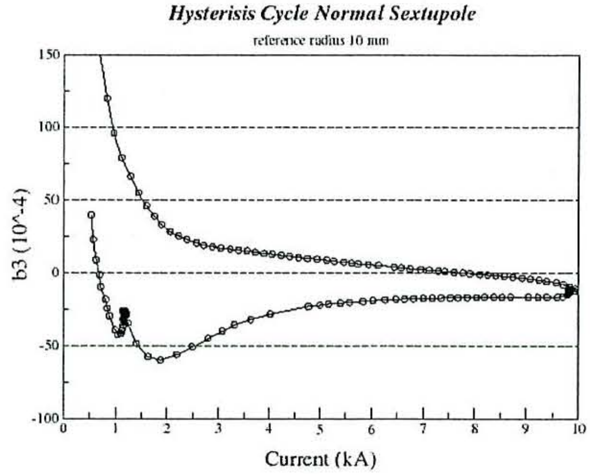


Fig. 7. Measured normal sextupole at 30A/s. The glitch at 1.2KA was a 15 min pause for snap-back measurements

In Fig. 8 the up-ramp and down-ramp dependences of the normalized integrated sextupole harmonic (b_3) are averaged to eliminate ramp-rate and magnetization hysteresis. The results for sever ramps are compared against the calculated values. The current dependence is caused by the manner with which nearby iron saturates, especially the iron, coil-winding pole. There is very good agreement on the shape, but the calculated values are systematically 5 units more positive than the measurements. The 1KA value on the first up-ramp was very negative because the magnet was ramped right after a cleansing quench.

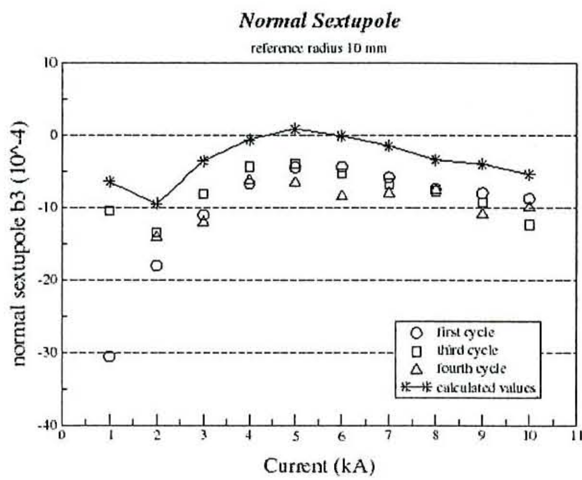


Fig. 8. The normalized integrated normal sextupole (b3) versus magnet current: An up-ramp/down-ramp average removes the ramp-rate and magnetization hysteresis effects.

Z-scan measurements were performed twice at 10kA. In Fig. 9 the measured values of the main dipole field B1 are reported together with the expected values. To fit the calculated values it was necessary to apply a multiplying factor 0.96 to the measurements, consistent with the 4% error previously measured (Fig. 6). The data also needed to be shifted 18 mm relative to the "center" position empirically determined by crude oscilloscope measurements. An 18 mm error was well within the uncertainty of this centering method.

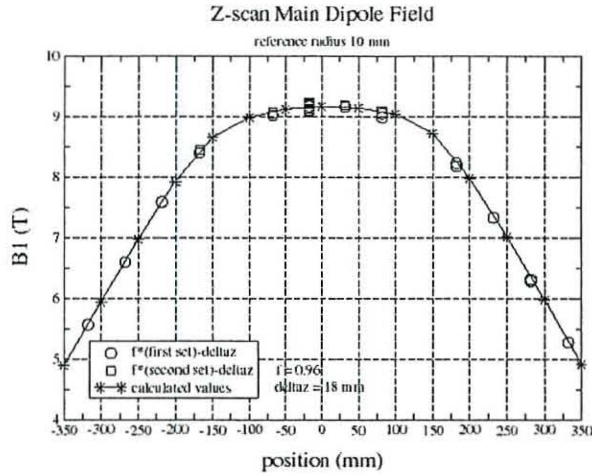


Fig. 9. Z-scan measurement of the main field component B1 as a function of position respect to the center of the magnet. To fit the calculations it was needed to apply a multiplying factor 0.96 and a position offset of 18 mm.

IV. DISCUSSION

The correlation between large numbers of stick-slip conductor movements and slow training is not new, having previously been observed in D20 and RD3b. What is new is the large number of large fast flux imbalance signals. This plus RD3c's slow, motion-triggered quench training suggests that something in the magnet was neither well clamped, nor easy to slip. Having most of its quenches and fast flux changes originating in the previously trained outer coils suggests that portions of these coils had not been restrained properly. This is also consistent with the large number of stick-slip movements that interminably repeated above 8KA. Furthermore, the huge accelerations that were observed immediately before an anomalously rapid resistance development (Fig. 3) suggests block slippages of many turns that triggered massively parallel quenching. It also raises the question whether RD3b's high coil stress may have relaxed the outer coil's pre-stress.

Conversely, the relative lack of quenches and stick-slip movements in the (virgin) insert coil supported the coil fabrication changes that had been instituted after RD3b's slow training, and the consistency of the ramp-rate sensitivity validates the consistency of the conductor's cabling and reaction treatments. The lack of outer coil fast flux imbalances could be interpreted as layer 3 and layer 4 moving as a solid block.

The systematically increasing discrepancy of the integrated fundamental relative to the 3D integrals (Fig. 6) is puzzling, especially with the exceptionally close agreement between the Hall probe and the 2D calculations. Even allowing a 2% error in the probe/amplifier's Turn*Area*Length*Gain*Bandwidth product, there is still a discrepancy of 2% that is unexplained. This discrepancy could be explored during a second thermal cycle.

The sextupole hysteresis at 10KA is believed to be caused by two processes: the high ramp rate (30A/s) and the magnetization of the inner coil conductor that has a sizable margin. The constant offset between the hysteresis averaged values and the calculated values is believed to have resulted from a difference between the cold conductor positions, and the calculated (warm) positions

V. CONCLUSION

RD3c has extended the series of successful magnet tests that have been designed to explore the feasibility of Nb_3Sn "common-coil" racetrack magnets for use in dual-bore, high-field accelerators. The experimental measurements confirmed the following: 1) Significant improvements in training are required before these coil configurations are considered "reliable magnets". 2) The ability to monitor and analyze "stick-slip movements, via existing voltage tap signals, may be very illuminating. 3) This tool may be the long awaited means for locating coil regions that require special attention before magnet designers can deliver reliably performing magnets, 4) The harmonic measurements validate our ability to measure, and predictably reduce, the geometric harmonics of existing high current density "common-coil" racetrack coils, well below the magnet's hysteresis. 5) That this compensation was accomplished with simple, appropriately fabricated, common-coil, flat racetrack insert correction coils is very encouraging.

Accelerator designers will need multiple demonstrations that simultaneously achieve of all important magnet features (bore-field, field-quality, low cost, and reliability) before high-field "common-coil" magnets will become the baseline for an accelerator design.

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